

# Concepts and pathways towards a carbon-neutral heavy industry in the German federal state of North Rhine-Westphalia

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## Abstract

The German federal state of North Rhine-Westphalia (NRW) is home to important clusters of energy-intensive basic materials industries. 15 % of the EU's primary steel as well as 15 % of high-value base chemicals are produced here. Together with refinery fuels, cement, lime and paper production (also overrepresented in NRW) these are the most carbon-intensive production processes of the industrial metabolism. To achieve the ambitious regional and national climate goals without re-locating these clusters, carbon-neutral production will have to become standard by mid-century.

We develop and evaluate three conceptual long-term scenarios towards carbon-neutral industry systems for NRW for 2050 and beyond:

- a first scenario depending on carbon capture and storage or use for heavy industries (iCCS),
- a second scenario sketching the direct electrification of industrial processes (and transport) and
- a third scenario relying on the import of low carbon energies (e.g. biomass, and synthetic fuels (like methanol) for the use in industries and transport.

All scenarios share the assumption that electricity generation will be CO<sub>2</sub>-neutral by 2050.

For all three scenarios energy efficiency, primary energy demand for energy services and feedstock as well as the carbon

balance are quantified. We apply a spatial-explicit analysis of production sites to allow for discussion of infrastructure re-use and net investment needs. Possible symbiotic relations between sectors are also included. The robustness of the three conceptualised future carbon-neutral industry systems is then analysed using a multi-criteria approach, including e.g. energy security issues and lock-ins on the way to 2050.

## Introduction

Global energy-related GHG emissions will need to be reduced quickly in the coming decades and may need to be close to zero or even net negative by the mid of the century to reach the Paris goal of limiting global warming to well below 2 °C with a significant probability (e.g. Rogelj et al. 2015, Edenhofer et al. 2014, Millar et al. 2017). Such a decarbonisation will require a massive transformation of the economy, in regions like the German federal state of North Rhine-Westphalia with strong coal- and oil-based industries and energy-infrastructure. We therefore believe there is a strong and urgent need to develop concepts and feasible pathways for the long-term decarbonization of industrial sectors and industrial regions (see also Lechtenböhmer et al. 2015 and Samadi et al. 2018). Such work could support policymakers and investors when deciding on investments and measures that determine the (re-)design of industry processes, energy supply and energy infrastructures, which are going to be in place for particular long periods of often 30 to 50 years.

North Rhine-Westphalia (NRW) has 18 million inhabitants and is the most populous state in Germany and very densely populated. Despite structural changes in the last decades, it has still extensive lignite mining, significant conventional (coal

based) power production, crude oil refining and a very large energy-intensive industry as it is home to around 15 % of the EU's primary steel as well as 15 % of high-value base chemicals production. Around one third of Germany's primary energy production and of its consumption take place in NRW, and about 40 % of the electricity is consumed there, while production is slightly higher, making the state a net electricity exporter (IT.NRW 2014). NRW also emits about one third of German greenhouse gas (GHG) emissions (305 MtCO<sub>2eq</sub> in 2012) or about 7 % of the EU's GHG emissions. Its total emissions are equivalent to those of Spain (LANUV NRW 2014, DEHSt 2014). The state is therefore a key region for meeting the national and European climate targets.

The scenarios analysed in this paper are based on earlier work in the context of an intensive stakeholder based scenario process for the drafting of the state Climate Protection Plan (cp. Lechtenböhrer et al. 2015). These earlier scenarios, however, described future energy systems, which hardly reach an overall GHG mitigation of 80 % compared to 1990 levels, and the industry sector reaching considerable lower mitigation levels (Schneider et al. 2014). In this paper, we expand the analysis and develop scenarios of almost completely decarbonised energy systems or even net negative emissions, by which we aim to add to the discussion of carbon neutrality.

In the following we describe three different prototypical future low carbon systems for the highly-industrialised region of NRW with a focus on the industry and transport fuel supply sector. Respective energy needs are balanced and *carbon accounting* was used to show the total carbon turnover of the three future energy systems. From today's point of view mixed forms of all three types seem to be more realistic than one of the pure images. Our hypothesis is, however, that infrastructures play an important role in the transition and that infrastructures often require a clear decision to go for one system instead of another.

Bottom-up as well as top-down optimisation models, which are widely used to analyse transitions in the energy system, have in general a poor representation of infrastructures. The electricity grid as one part of the infrastructure is taken into account in some bottom-up models, but they have a narrower focus on the electricity system only.

The aim of this paper is to address possible co-evolution of energy supply, infrastructures and energy demand and derive a geographically explicit view on possible future low carbon energy-industry-infrastructure systems and the transitions towards them. The three system prototypes shall be used to display advantages and disadvantages of each type and to hint at possible barriers in the transition from today's system into the future system, and to detect possible co-evolution and lock-ins.

The three future systems each represent one individual strategy, all of which are discussed in current scenario literature:

- Carbon Capture and Storage (CCS) in industry ("ICCS" case),
- indirect electrification (Power-to-X, "P2X" case) and
- direct electrification ("all-electric" case)

CCS is a very prominent strategy in international discussion on GHG mitigation in the power and industry sectors. The IPCC (Fischelick 2014a) stresses the importance of this strategy and

many models including IEA's energy system model indicate CCS as the most economic strategy to reach ambitious climate protection goals (e.g. IEA's so-called "Beyond two degrees scenario" (BY2DG); IEA 2017). A recent synthesis of country specific deep decarbonisation pathways, also highlights the prominence of CCS as a strategy (DDPP 2015).

*Electrification* is an important strategy in scenario literature as well. However, the production of hydrogen from water electrolysis is often focussed mainly as a "by-product" of the extension of renewable electricity production to make use of "excess electricity" production, at least for developed regions outside the sunbelt of the globe. Battery cars are another option, which is obviously far more efficient than the use of internal combustion engines (ICE). Deep cost-cuts in renewable electricity production have now made electrification more attractive and the discussion proceeds from merely assuming the use of "excess electricity" towards scenarios assuming additional electric capacities to allow for deeper decarbonisation via electrification.

The electrification discussion takes two directions (see e.g. Lechtenböhrer et al. 2017): The first is an *indirect* use of electricity converting electricity to another (hydrogen based) energy carrier (P2X<sup>1</sup>), which may offer similar properties as natural gas or oil products. The second way of electrification is converting electricity *directly* to useful energy, e.g. in battery electric vehicles (BEV), heat pumps and electric boilers or furnaces as discussed for the European heavy industry in Lechtenböhrer et al. (2016).

*Biomass use* is the forth core strategy discussed in decarbonisation literature. We did not develop a dedicated scenario for it but regard this strategy in all of the three systems. In fact the all-electric scenario does without biomass in final energy demand but requires on the other hand large amounts of renewable electricity in the inland, so biomass use could then be allocated to domestic electricity generation.

## Methodology: System boundary, calculation and data

The analysis describes a stationary state of a low carbon energy-industry-infrastructure system for the federal state of NRW. Depending on the ambition of GHG mitigation such a system could be in place by 2040, 2050 or even 2060. We used 2050 as a scenario year using 2050 scenario data from other studies.

The system analysed consists of the main sectors of the energy system, i.e. the manufacturing sector (incl. the supply of fuels), the transport sector and the building sector. But only the manufacturing sector and the transport sector were analysed scenario specific. The main reason for this is the strong interconnection of chemical industry and transport sector via the refineries and the petrochemical sector as well as a possible competition for scarce energy resources like biomass – making an integrated assessment necessary. Energy demand and carbon balance of the production of thirteen energy intensive materials and four different fuels were calculated bottom-up regarding process-specific data. Other energy demand (e.g.

1. Power-to-Heat (PtH) is also discussed in the context of P2X, although there is no conversion to another energy carrier there. In this paper we will use the term P2X exclusively for the indirect use of electricity.

**Table 1. Activity data used in the scenario calculation.**

	indicator	activity 2015	assumed activity in the future (2050)	Source
mobility				
passenger cars	bill. vehicle-km	126.7	81.8	Görner et al. (2018)
light-duty vehicles	bill. vehicle-km	7.3	12.0	
heavy-duty vehicles	bill. vehicle-km	10.3	10.2	
aviation passengers	bill. passenger-km	27.2	26.3	
aviation freight	bill. tonne-km	1.4	3.1	
inland navigation	bill. tonne-km	25.2	58.1	
buildings				
buildings (residential and others)	TJ	N/A	295.7	Görner et al. (2018)
industry				
primary steel	Mt steel	15.1	15.1	IT.NRW (production statistics at federal state level) and own assumptions based on trade association data
secondary steel	Mt steel	2.3	2.3	
hot rolling of steel	Mt hot-rolled coil	13.6	13.6	
primary aluminium	Mt aluminium	0.2	0.2	
secondary aluminium	Mt aluminium	0.2	0.2	
hot-rolling of aluminium	Mt hot-rolled coil	2.0	2.0	
high-value (petro-)chemicals	Mt HVC	6.2	6.2	
ammonia	Mt NH3	0.6	0.6	
cement	Mt cement	9.5	9.5	
lime	Mt lime	1.6	1.6	
paper	Mt paper	4	4.0	own assumption derived from HVC production
flat glass	Mt flat glass	0.5	0.5	
container glass	Mt container glass	0.1	0.1	
steam (cross-cutting)	TJ of steam	98.2	88.4	
other high-temperature heat demand	TJ HT-heat	35.8	35.8	
other (low-temperature) heat	TJ heat	317.1	285.4	
other electricity demand	TJ electricity	85.5	72.7	
amount of plastic waste for chemical recycling	PJ of methanol from plastic waste (which is not suitable for mechanical recycling)			

Source: Own table.

for less energy intensive industry processes and buildings) was taken from a climate protection scenario developed by the Wuppertal Institute and described in Görner et al. (2018). The carbon balance does not only account for net energy related CO<sub>2</sub> emissions to the atmosphere (which is a default feature of any state-of-the art energy system model), but accounts the total carbon turnover within the energy system, including fossil, atmospheric as well as biogenic carbon. So, carbon stocks in products or geological storages can be considered.

Calculation for the three future systems was carried out in a spreadsheet model using physical production quantities in industry and mileage of cars and lorries as activity indicators (see Table 1).

Activity indicators were multiplied with suitable energy intensity and carbon intensity indicators to derive energy and CO<sub>2</sub> flows. Industry (incl. fuel supply) intensity indicators were extracted from Wuppertal Institutes WISEE ESM industry stock database (see e.g. Schneider et al. 2014), where data on today's standard technologies, BAT as well as future technologies (developed and proven but not economic yet) are available. These indicators have been used and validated before in various projects analysing production, energy and GHG statistics and discussed with stakeholders and experts.

Technical indicators for the transport sector were derived from JRC (2013) for a generic passenger car type (for the years 2020+) and from Wietschel et al. (2017) for light- and heavy-duty vehicles (scenario car 2030). Indicators for aviation and navigation were extracted from the scenario studies described in Görner et al. (2018).

For the discussion of geographical aspects (see below) GIS data from the WISEE industry stock database as well as CO<sub>2</sub> emission data from EEA's e-prtr database<sup>2</sup> have been used to develop suitable maps.

## Scenario Design

We combined the different scenario specific assumptions for industry and transport with only one common scenario for buildings in NRW taken from another study (Görner et al. 2018), which consists of a mixed system with heat pumps, district heating and gas supply and is thus equal across the three scenarios.

Energy efficiency improvements are regarded in all three scenarios as best-available technology applications have been assumed as standard for reinvestment in all applications.

Electricity generation was assumed to be 100 % renewable and thus carbon neutral, but in the iCCS Scenario there are two exceptions: Industrial CHP which was assumed to be fossil-fired (with CCS) and electricity production from waste incineration (with CCS), both delivering a part of the electricity demand in that scenario.

To reduce complexity, we assumed the production (in physical terms) of energy intensive goods to be equal to today's production. Other activity data like "other energy need" of industry or the mileage of cars and planes were taken from a NRW

2. See <http://prtr.ec.europa.eu>.

Table 2. Matrix of technologies used in the three scenarios.

energy service	ICCS	P2X	all-electric
transport			
Passenger cars and LDV	bio-methane, imported	methanol ICE (imported)	battery-electric vehicles
HDV	biodiesel, imported	methanol ICE (imported)	trolley with methanol fuelled range extender
inland navigation	biodiesel, imported	methanol (imported)	methanol
aviation	syn-kerosene, imported	syn-kerosene, imported	syn-kerosene
<b>buildings</b>	same assumptions for all cases		
<b>industry</b>			
primary steel	smelt reduction with CCS	DRI with hydrogen (imported)	DRI with hydrogen
plastics and solvents	steam cracking with CCS	power-to-plastics via imported methanol	power-to-plastics via methanol
large scale industrial ovens	natural gas and coal oxyfuel burners with CCS	biomethane, imported	electric ovens (power-to-heat)
steam	natural gas-CHP with CCS or bio-methane (imported) fired boilers	biomethane, imported	electric boilers, high-temperature heat pumps*
other (heat)	biomethane, imported	biomethane, imported	electric boilers, high-temperature heat pumps*
<b>Electricity generation</b>	renewable, centralized CHP with natural gas+CCS and waste incineration+CCS	renewable	renewable

\* High-temperature heat pumps could be driven by excess heat from industry processes or geothermal heat.

Source: own assumptions.

specific energy scenario by the Wuppertal Institute described in Görner et al. (2018).

Table 2 sums up the technology assumptions for each of the three scenarios. The corresponding storyline of each is described below.

#### SCENARIO ICCS

The ICCS scenario is the one most similar to today's system as it predominantly builds on technologies used today and adds CCS as an end-of-the-pipe technology. For these parts of the industrial production stock have to be adapted to facilitate the adoption of carbon capture at capture rates close to 100 %. One example is primary crude steel, which is today produced in the blast furnace/blast oxygen furnace (BF/BOF) route. This will be changed to the smelt reduction process in the scenario, which has a higher overall efficiency and yields higher concentration of CO<sub>2</sub> in exhaust gas streams allowing for a more efficient capturing of CO<sub>2</sub> at high capture rates than the BF/BOF route. Another assumption is, that *oxyfuel burners* will replace existing burners in industry ovens of the glass and cement industry. Such a replacement should be completed towards the end of the scenario horizon, but other (retrofit) carbon capture options may phase-in earlier to facilitate an early phase-in of CCS.

For *transport*, there is no realistic option to go for CCS, so together with energy efficiency improvements, a conversion to biodiesel or biomethane is assumed. Regarding the strong growth expected in aviation we did not consider biomass use there. First generation biofuels cannot be used in aircraft turbines anyway, so there has to be supplied some kind of synthetic kerosene.

An alternative option often described in scenario literature (e.g. IEA 2017) would be to compensate fossil energy use in transport by adopting biomass-CCS in power plants (BECCS). The latter with net-negative emissions then allows for net car-

bon neutrality. As we excluded CCS for power plants we did not consider this option.

As mentioned above we assumed the adoption of CCS in *industrial CHP* as one exemption of power plant CCS in this scenario. So the significant steam demands in NRW's chemical parks and paper mills can be supplied via fossil fuels and CCS allowing for some self-production of electricity.

*Hydrocarbon products* (e.g. plastics) are produced like today based on oil derivatives as feedstock. To ensure carbon neutrality the products are burnt after usage in waste incinerations with CCS providing additional electricity (second exception from power plant CCS). Another option also consistent with the ICCS case would be to use lignite from NRW mines as a carbon source for hydrocarbons. However, because of the lignite's hydrogen to carbon ratio lignite use would lead to additional CO<sub>2</sub> (which would have to be stored) or an extra need for hydrogen.

#### SCENARIO P2X

The P2X scenario also has many similarities with today's energy supply to the final consumer, but some major differences to it. Transport fuels in this scenario remain liquid. For complexity reduction, we assumed synthetic RES-based methanol to be the universal "reference" energy carrier in this scenario, which is assumed to be traded on the world market, shipped to Europe via tankers and fed into pipelines to reach the NRW market.

The RES-based methanol is assumed to be produced in the world's sunbelt (e.g. North Africa, Middle East, Australia) using electricity from cheap wind and solar sources and CO<sub>2</sub> from the air. Methanol can be used in modified gasoline or diesel engines in cars and lorries. For aviation, synthetic-kerosene use is assumed (as in the other two scenarios). This could either be imported or derived from methanol via hydrogenation in a plant at a sea port (e.g. Rotterdam) or within NRW.

Steam demand of industrial parks and paper mills is supplied with methane-fired boilers (without electricity cogeneration). We assume that the existing gas grid is used to deliver bio-methane (i.e. biogases derived from wooden biomasses and conditioned to the specifications of the NG-grid to the industrial customers). Bio-methane is imported via existing NG systems, e.g. from Eastern Europe.

The new reference energy carrier methanol is also used to supply hydrocarbon based materials (e.g. plastics and solvents). The scenario assumes that the imported methanol is processed in NRW to supply olefins and aromatics, which are the crucial building blocks in organic chemistry. Another option could be to directly import olefins like ethylene and propylene via ship and (partly existing) pipelines.

As the *gasification of plastic waste* is a quite efficient way to supply syngas for methanol production (Brems et al. 2013), we assume that gasification and the conversion to methanol will be located at the existing petrochemical clusters in NRW.

NRW is the most important primary steel producing state within Germany. In this scenario, we assume that steel production is shifted to hydrogen-based direct reduction of iron ore to sponge iron and further processing to crude steel in an electric arc furnace (Fischedick et al. 2014b). To meet the hydrogen demand of steel industry (and some additional need in chemical industry) hydrogen is imported to NRW in this scenario.

#### SCENARIO ALL-ELECTRIC

The scenario “all-electric” assumes the largest changes in infrastructure and technology stocks within the set of scenarios analysed in this paper: The complete road transport system (i.e. all cars, buses and trucks) as well as the complete industrial production stock is assumed to be converted to the use of a different energy carrier, i.e. electricity. For some applications reinvestments in electric appliances will be cheaper than conventional technologies. Especially electric ovens typically have a simpler design and can be operated in a more energy efficient way than ovens relying on burners (see e.g. Schüwer et al. 2018, Guminski 2015).

However, it is most obvious that such a radical transformation of the energy system would also need new infrastructures, i.e. a stronger electricity grid on all voltage levels (including a Pan-European high voltage DC line system) as well as additional storage capacities for electric energy.

In the system sketched here NRW also imports electricity to produce methanol domestically for material supply, which is a rather radical assumption. As this is an indirect way of using electricity anyway, we could have also assumed an import of this P2X product without destroying consistency of the all-electric picture, but the reason for assuming inland production was to get an estimation about the maximum possible electricity imports when keeping industrial value added within NRW as much as possible.

#### Carbon balance

Figure 1 shows the carbon balances of the three cases, indicating the annual carbon turnover within the energy and product system (indicated by the height of the “energy system box”). Carbon turnover can be defined on the *source side* as

- the amount of carbon (CO<sub>2</sub> equivalent) in the extraction of fossil material (fuels, limestone) *plus*
- carbon (CO<sub>2</sub> equivalent) imbedded in (plastic) waste returned to the energy system *plus*
- CO<sub>2</sub> taken from the atmosphere via biomass cultivation or direct air capture (DAC).

On the *side of the sinks* the carbon turnover is mirrored by

- CO<sub>2</sub> (and CO) emissions – incl. from biogenic sources *plus*
- storage of carbon in products (i.e. plastics<sup>3</sup>) *plus*
- geological storage of CO<sub>2</sub> (CCS).

The “all-electric” scenario (displayed at the right side of the figure) is obviously the only real *low carbon* case – the other two are in contrast *net low carbon*. Carbon turnover in the *all electric* scenario amounts to 31 Mt/a and is restricted to process related carbon use and hydrocarbon material use, especially stock exchange and stock increase in plastic goods (19 Mt/a). Due to the overall assumption of a mixed system in the building sector, which is valid for all three scenarios, there is also some use of biogas with corresponding CO<sub>2</sub> take-out from the atmosphere and respective emissions.

In all three scenarios, there is the same amount of carbon in (plastic) waste returning to the energy system after expiration of use (6 Mt/a). The amount of carbon bound in annual new production of plastic goods is also assumed to be the same in all three scenarios (19 Mt/a), implying a massive annual plastic stock increase similar to today’s levels.<sup>4</sup>

Process related CO<sub>2</sub> emissions at an amount of 7 million tons of CO<sub>2</sub>/a from carbon use in secondary steel production and aluminium electrolysis, lime and cement clinker production as well as glass production are equivalent in all three cases.

Apart from these similarities the differences prevail: In the ICCS case most of the carbon entering the system is of fossil origin, 90 % of it being compensated for by the application of CCS.<sup>5</sup> CO<sub>2</sub> emissions from fuel use in internal combustion engines and decentralised heat supply is compensated by biogenic carbon use, so the net balance of CO<sub>2</sub> outtake from the atmosphere and respective CO<sub>2</sub> emissions of these applications is neutral. The remaining *net CO<sub>2</sub> emissions* represent the total net flow between fossil bound carbon and carbon in the atmosphere within one year. They are visible as the delta between the two dotted lines. The black-dotted line indicates the level of fossil CO<sub>2</sub> input and the green one the level of CO<sub>2</sub> storing. If the level of fossil input exceeds the level of storing, there are annual net emissions.

In the ICCS case the net (positive) emissions represent the share of non-captured fossil CO<sub>2</sub> flows in industry. It was stated already earlier in this paper that the net emissions in this case could be compensated by the application of BECCS, e.g. by bi-

3. Storage in wood products or wood derived products like paper is also relevant in principle (if there is a net stock increase) but was not regarded here.

4. The assumption about continued stock increase is rather conservative. With circular economy playing a more important role stock increase could be gradually reduced leading also to lower energy demands for plastics production.

5. The net balance of CO<sub>2</sub> input in waste and CO<sub>2</sub> storing in products was subtracted from the fossil CO<sub>2</sub> input before calculating the share.

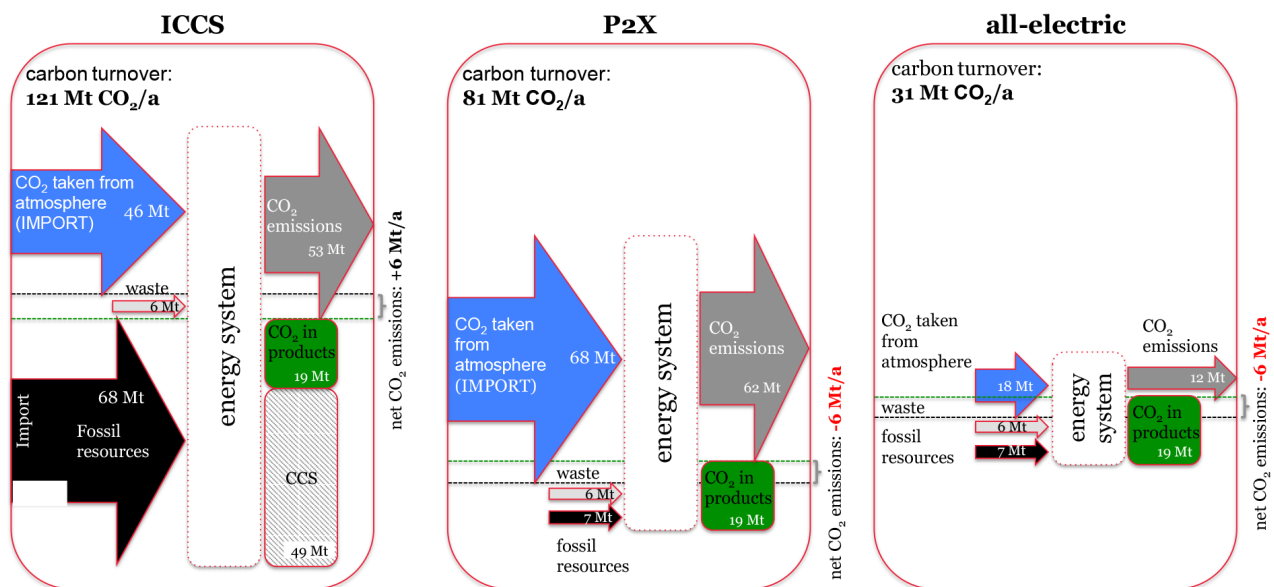


Figure 1. Carbon balances of the three decarbonisation worlds (annual flows). Source: own figure.

ogas instead of natural gas firing in industrial CHP plants with CCS.

The *PtX* case displays almost no entry of fossil carbon into the system. But also the gross carbon turnover is lower than in ICCS, which can be attributed to the following issues:

- Hydrogen is used in primary steel production instead of coal/coke,
- Olefin and aromatics production is shifted from steam cracking (with attributed firing of a part of the fossil feed-stock) to methanol-based production,
- No CHP (no gas use for electricity generation in combined-cycle),
- Higher “carbon efficiency” in transport due to methanol use instead of biodiesel and biogas.

The net negative CO<sub>2</sub> emissions of 6 Mt/a indicate that the “storage” of carbon in goods (via net stock growth) outweighs fossil entries in the system by carbon use in the metal industry and limestone use. If the net stock increase in plastic goods was substantially lower also net positive CO<sub>2</sub> emissions could occur.

### Energy system and infrastructure implications

Even after the phase-out of hard coal mining in NRW in 2018, lignite mining and extensive infrastructures to transport and convert energy will remain. Hard coal for power plants and steel production is shipped in big vessels along the River Rhine to the power plants and steel mills. Natural gas is imported via a strong gas grid and crude oil and liquid as well as gaseous oil products are transported to and from the three world scale refinery sites via two pipelines connecting the NRW refinery sites with the Port of Rotterdam as well as the South-West of Germany. NRW is an important net exporter of electricity (especially to the rest of Germany and the Netherlands). So there is already a strong electricity grid connecting power plants, energy intensive industries (like primary aluminium produc-

tion) and the neighbouring regions. Additionally, a regional hydrogen grid interconnects the relevant clusters of refineries and the chemical industry in the Rhine-Ruhr region.

In the following we make a first assessment of energy infrastructure adaption needs for the three deep decarbonisation scenarios discussed above and add one additional sensitivity “*all-electric* + *P2X import*” to the analysis (described below). Quantitative analysis is restricted to annual *net import flows*. These can be used as a first order indicator for adaption needs in the main transmission infrastructures. Subsequently we discuss geographical aspects of sources and sinks qualitatively, giving insights to scenario-specific intra-NRW resource flows and respective infrastructure requirements.

### NET FLOWS OF ENERGY

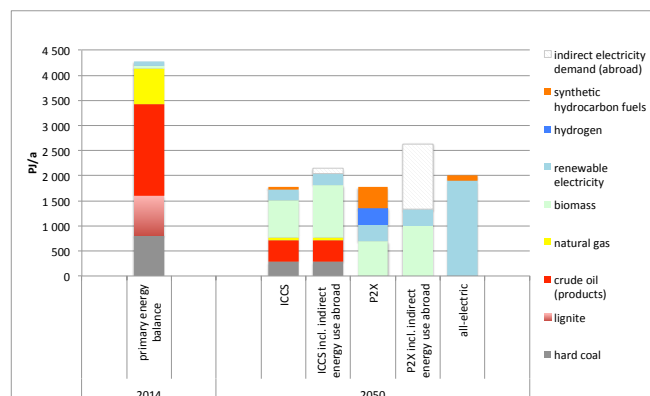
All of the scenarios show that future decarbonised energy systems’ primary energy balances will significantly deviate from today’s situation as displayed in Figure 2a. The primary energy supply to the three sectors transport, industry and buildings shows significant energy demand reductions in all three scenarios compared to today’s energy situation plus strong differences in the role of the energy carriers.

The *ICCS* strategy generally substitutes oil use in transport by using (imported) biomass, applies CCS to the great centralized points of energy use and uses biogas to meet the rest of decentralized demand in industry and buildings. Therefore biomass use grows substantially, but the amount of growth is still in line with other scenarios, that rely strongly on biomass and CCS (e.g. the B2DS in IEA 2017).

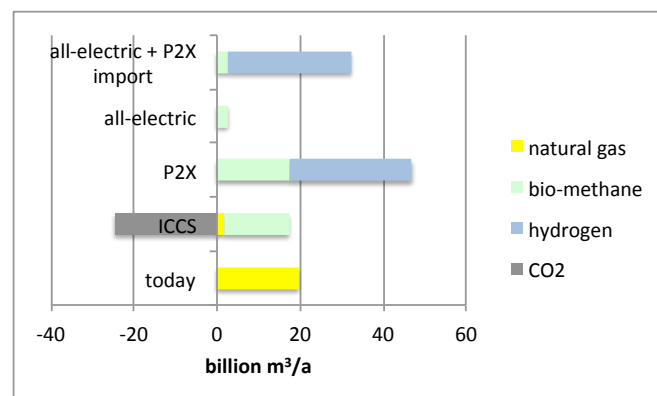
The *P2X* scenario assumes a mix of biomass and synthetic electricity based fuels with the same amount of biomass used as in “*ICCS*”, but with a differing structure, using more biomass in industry and less in the transport sector (not displayed in the figure).

Finally, the *all-electric* strategy is as monolithic as the name of the scenario suggests. Here an amount of over 500 TWh (1,800 PJ) of electricity demand in NRW needs to be covered, which implies massive imports. NRW’s environmental agency

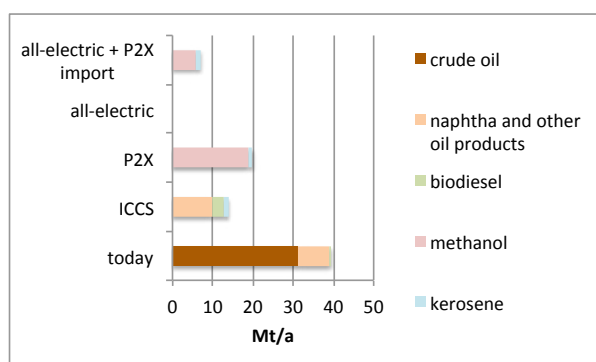
**Figure 2a. Primary energy balance of energy and feedstock supply in transport, industry and buildings for NRW.**



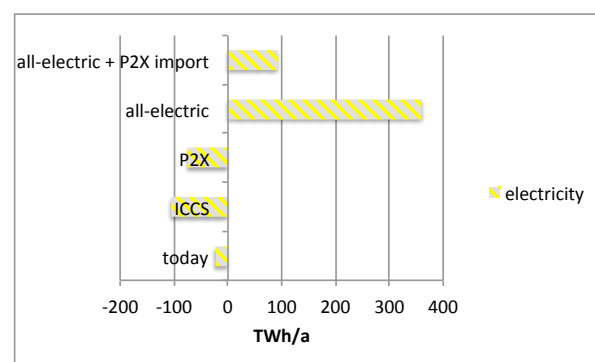
**Figure 2b. Gas net imports.**



**Figure 2c. Hydrocarbon liquids net imports.**



**Figure 2d. Electricity net imports.**



**Figure 2. NRW primary energy balance and annual net energy related resource import flows in the three cases compared to today. Source: own figure, based on IT.NRW (2017) and own calculations.**

assessed that there is a domestic potential of 169 TWh of renewable electricity generation, i.e. 83 TWh from wind, 72 TWh from PV, 13 TWh from biomass and 0.6 TWh from hydro power (LANUV NRW 2012, LANUV NRW 2013, LANUV NRW 2014b, LANUV NRW 2017). Geothermal energy potential was also assessed by LANUV (2015), but the total NRW potential was allocated to heat supply. So, the technically feasible potential is around one third only of calculated demand in the scenario.

The changing primary energy balance implicates also changes in energy import/export balances (see Figure 2b–d): Today NRW imports 39 billion standard cubic metres of natural gas annually (Figure 2b), but also exports 20 billion m<sup>3</sup>.<sup>6</sup> In the transmission grid natural gas is usually compressed to around 100 bar to use the pipelines more efficiently. The resulting annual net import flow amounts to 20 billion standard cubic metres per annum (see Figure 2b)<sup>7</sup>.

Two scenarios (ICCS and P2X) exhibit a similar amount of *gaseous* (methane) import needs in the future (sum of natural gas and bio-methane), which is almost as high as today's natu-

ral gas import. But they both require additional gas carrying pipeline infrastructures: Depending on the time of CCS phase-in NRW CO<sub>2</sub> storage sites in the ICCS case might be already filled in this scenario by 2050, so the total annual CO<sub>2</sub> amount to be stored (49 Mt/a or 25 billion standard cubic metres/a) has to be “exported”, e.g. to the North Holland gas fields or Northern German saline sediments. The P2X scenario on the other hand requires a massive import of hydrogen. As the existing natural gas grid is still busy with the transport of methane (and thus cannot be converted) an additional hydrogen pipeline (or grid) is needed connecting the steel mills and refineries at the River Rhine with possible hydrogen generation (e.g. at the North Sea coast) or import hubs (e.g. Rotterdam). In contrast, in the *all-electric* case gas infrastructure will merely not be needed anymore. The remaining gas demand (of the building sector) might even be supplied by NRW biogas plants (not part of the analysis).

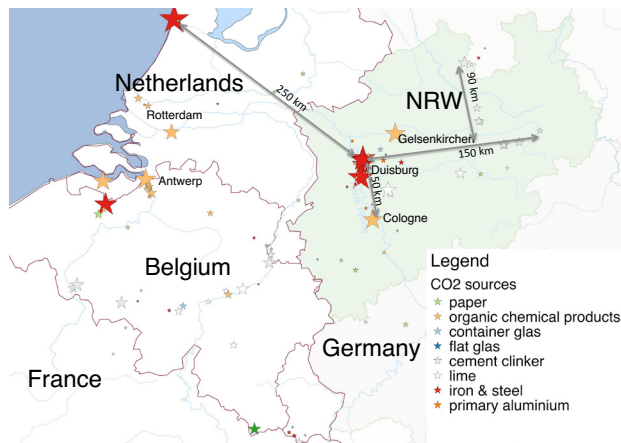
Almost 40 million tons of *hydrocarbon liquids* were imported to NRW in 2014 (Figure 2c) via pipeline, inland navigation and railways, pipelines being the main carrier for standard liquids like crude oil, naphtha or kerosene. Modal shift from passenger cars and trucks to railways and inland navigation as well as technical energy improvements in the fleets are the main drivers for a shrinking demand in liquid fuels in the scenarios. So the existing infrastructure would suffice to carry future imports of liquid fuels in all scenarios analysed if the crude oil pipelines

6. The values are taken from NRW's energy balance (IT.NRW 2017), where a lower heating value of 35.182 kJ/m<sup>3</sup> is applied. A norm cubic metre is defined as the volume of a gas under a pressure of 1.01325 bar at 0° C.

7. Ethylene imports are also relevant, but the amounts are not reported in the regional NRW energy statistics. Trade statistics (which account chemical products as well) are only available at the federal level.



## Scenario ICCS



## Scenario P2X



## Scenario all-electric

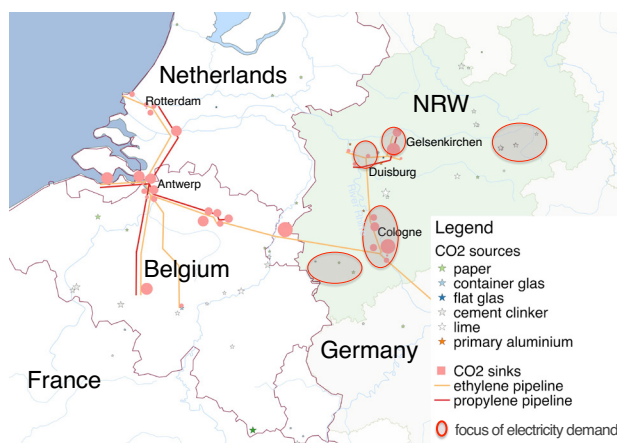


Figure 3. NRW maps on critical infrastructures in the three scenarios. Source: Own maps based on Wuppertal Institute's WISEE ESM Industry database and EEA's e-prtr database.

are converted to the respective energy carriers like oil products or methanol. In the scenario *ICCS* still naphtha derived from fossil oil is imported to produce petrochemicals in NRW steam crackers. Again, the *all-electric* scenario will by 2050 not require any pipelines for the import of liquids, so also the existing oil pipeline import infrastructure could become mothballed.

As expected, the analysis of *electricity* import needs reveals just the opposite conditions (Figure 2d): massive net imports of electricity in the all-electric-case, whereas in the other two scenarios NRW would not even have to make full use of the domestic electricity generation potentials. It is most obvious, that such a combination of relatively expensive renewable electricity generation within NRW (offside the coasts and offside the sunbelt) and simultaneously not using the flexibility features of P2X within the state is not sensible. Probably under such scenario conditions as described in *ICCS* and *P2X* the NRW potential of renewable electricity generation would not be exploited to the full degree – or would be complemented by a smaller scale inland use of P2X (e.g. for Power-to-Heat in industry), thus reducing the amount of net electricity exported.

The three graphs (Figure 2b–d) share one finding regarding the *all-electric* case: Existing infrastructure cannot boost

such a development. Existing gas and liquids infrastructures will become obsolete by 2050 whereas today's electricity grid would be by far too weak. However, as stated above, import of P2X products instead of domestic production from imported electricity would result in lower electricity demand but also fit the general storyline. We therefore added the "*all-electric+P2X import*" sensitivity, where such an import of P2X products (i.e. methanol and hydrogen) is assumed. On the side of final energy demand all the technologies remain the same as in the all-electric main case.

The sensitivity exhibits a much better fit to existing infrastructures: the existing gas transmission infrastructure could be partly used to carry hydrogen and the oil products pipeline could be converted to methanol transport. If NRW would no longer be an energy transit region (depending on future developments in Southwest Germany) use of today's available gross import capacities (at least the amount of 39 billion m<sup>3</sup> imported into NRW in 2014) would mean a doubling of net import capacities.

Net electricity import demand remains high in the sensitivity "*all-electric+P2X import*" though and probably will require grid expansion still, but to a much lower extent than in the *all-electric* main case. More precise estimates of grid adaption



needs would need additional simulation by models with a high time resolution.

Taking primary energy use of the total supply chain into account, the sensitivity shows higher overall electricity demand as it does not make use of domestic CO<sub>2</sub> sources (like in the all-electric case) e.g. in the cement industry and relies on the less efficient direct air capture process (DAC) instead, which is assumed as a reference application for P2X production abroad.

It can be concluded, that each scenario faces different infrastructure challenges regarding the import of energy carriers, that can be clearly attributed to the respective main strategy: In the *ICCS* case there is the need to develop a CO<sub>2</sub> grid, in the *P2X* case a hydrogen import grid has to be developed and in the *all-electric* case the electricity grid has to be significantly expanded.

#### GEOGRAPHICAL ASPECTS

A discussion of geographical aspects of the three scenarios' infrastructure requirements can be based upon the maps given in Figure 3. The German federal state of NRW (green highlighted area) is shown together with neighbouring Netherlands and Belgium to demonstrate existing and possible future interconnections, synergies or competition of sites. The three maps focus on the "critical" infrastructures of the respective scenario as identified in the section before: CO<sub>2</sub> in the *ICCS* case, hydrogen in the *P2X* case and electricity (as well as NRW internal CO<sub>2</sub> flows) in the *all-electric* case.

The *ICCS* map shows that the CO<sub>2</sub> sources to be collected are concentrated in the western part of NRW along the River Rhine (metal and glass industry, steam cracking). However, relevant amounts of CO<sub>2</sub> also result from the cement clinker plants in the North and East of the state. A possible CO<sub>2</sub> hub to be connected to NRW could be the steel plant at Ijmuiden, just 250 km North-West of NRW's steel cluster at Duisburg. The chemical clusters at the Antwerp and Rotterdam port could also be possible hubs if they are developed early enough, but they are more far away from the considerable CO<sub>2</sub> storage capacities in the North of the Netherlands as well as offshore in the North Sea. Within NRW the steam cracker sites at Cologne and Gelsenkirchen as well as the cement sites could be connected to Duisburg by a backbone grid of ca. 300 km length. South west of Cologne there are some minor sources of CO<sub>2</sub> (paper mills, glass industry and non-ferrous metals) but probably still important enough to develop a collection pipeline.

For the *P2X* scenario hydrogen import infrastructure was identified to be critical. In fact, the enormous hydrogen needs identified with a clear hotspot at the primary steel plants at Duisburg would require a hydrogen pipeline with a diameter of around 100 cm when operated at 100 bar.<sup>8</sup> Existing hydrogen pipeline grids in Europe have a considerable lower cross section of 10–20 cm (Air Liquide grids in BeNeLux and in the NRW Rhine-Ruhr area). To allow for flexibility operators often admit pressure ranges between 20 to 100 bar. Such a flexible operation would even require a higher cross section or double tubes. At Duisburg the pipeline could be connected to the existing Air Liquide operated Rhein-Ruhr hydrogen distribution network (which could be augmented in capacity) interconnecting the

cluster Gelsenkirchen/Marl with the Cologne chemical clusters. The existing ethylene pipeline from Antwerp could deliver olefins directly to the petrochemical clusters at Cologne and Gelsenkirchen/Marl and thus reduce methanol transport needs (transferring olefin production from NRW to coastal sites), but actually provide no alternative for hydrogen import, which is needed in the scenario to make locally collected carbon from plastic waste fully available for a chemical recycling.

The *all-electric* case exhibits several hot spots of electricity consumption, but actual locations particularly of electrolyzers, which will be a major bulk electricity consumer, could be optimized to minimize expansions in the distribution networks. Electrolyzers could be operated at intersection points of high voltage electrical grids and existing hydrogen or the ethylene/propylene grids. Other hotspots are rather locally tied to existing sites like the cement industry with their limestone quarries or existing rolling mills of steel and non-ferrous metals industry. The existing natural gas grid would be hardly used anymore and could be converted to a NRW CO<sub>2</sub> distribution network to interconnect industrial CO<sub>2</sub> sources in the East (in this scenario especially the lime and cement industry) and possible CO<sub>2</sub> sinks in the West. The CO<sub>2</sub> processing plants (i.e. methanol plants) could be located at existing ethylene/propylene pipelines.

The adaption of existing infrastructure might be costly, but the low public acceptance of new infrastructures observed also in NRW (e.g. of a 30 km carbon monoxide pipeline planned to connect two chemical industry sites) adds additional benefit to a conversion of existing infrastructures compared to a green-field investment.

#### Conclusions

Achieving deep decarbonisation will only be feasible if all sectors of the economy, including the so called difficult to decarbonise sectors reduce their GHG emissions towards zero by the mid of the century or soon thereafter. Energy intensive processing industries play a particularly important role in that context. In this sector deep decarbonisation pathways impose a combined technological, economical as well as infrastructural challenge. New and often disruptive technology needs to be developed and implemented, much of which is still in early development stages. These technologies also typically require the supply of large amounts of clean energy. North-Rhine Westphalia, with its share of over 10 % in European energy intensive industries, is a good case to analyse these challenges, as processing industries are typically highly geographically concentrated, often together with fossil energy industries, which were one of the main reasons for the location of many of these industries when they were developed. Our analysis shows that deep decarbonisation strategies for such industrialised regions impose significant infrastructural challenges, as they need supply of clean energy supply and/or the discharging of sequestered CO<sub>2</sub>.

From a methodological point our analysis shows that deep decarbonisation scenarios for industry and industrial regions need to take into account also the so called non-energetic energy demand for feedstock of the chemical industry as well as carbon balances, that not only cover emissions to and removals from the atmosphere but also the carbon stock in industrial products.

8. This calculation was derived by assuming a throughput rate of 15 m/s.

Our three scenarios show that very different future visions are in principle possible for deeply decarbonising heavy industrial regions, with CCS, P2X or electrification being the main strategies. Their carbon balance, however, shows that, while all leading to close to zero net CO<sub>2</sub> emissions, the first two strategies would reduce the overall carbon balance of NRW by around two thirds or more (from more than 300 Mt today to 121 or 81 Mt in 2050), thus rather being net low carbon while only the electrification scenario reduces the overall carbon balance by more than 90 % to an annual 31 Mt.

Besides the technological and economical challenges to realise deep decarbonisation scenarios for industrial regions, which are not analysed deeper in this paper, our analysis of the respective infrastructure demand clearly shows that all of them impose their own infrastructure challenge. These infrastructural challenges seem to be inevitable – in spite of the strong decline in primary energy demand by around 50 % in all three scenarios.

For NRW only the existing pipeline infrastructure for oil and other liquid hydrocarbons seems to be more than sufficient or even over dimensioned for all three of the scenarios. Future imports of synthetic, RES based fuels or chemical feedstock will have significantly lower volumes than current imports of fossil products, mainly due to the strong electrification of road transport and the space heating sector foreseen in all scenarios. Gas infrastructures also already have sufficient capacities to supply bio-methane in the ICCS and P2X scenario. However, for the envisioned additional hydrogen imports of the P2X scenario, a dedicated infrastructure would need to be developed. In the *all-electric* scenario gas infrastructures become largely obsolete but might be converted into hydrogen infrastructures as the variant of that scenario shows. It is important to note, however, that the mere fit of the available transport volumes needs also to be amended by a check of the related geographical sources for the new energies. As the bulk of the gas and oil pipeline grid also today is supplied from the Netherlands and particularly from the Rotterdam seaport, in the case of NRW there could be a good fit also in the future, with the exemption of bio-methane, which might increasingly be imported from Eastern European supplies. A completely new infrastructure would have to be developed for the ICCS scenario. A dedicated CO<sub>2</sub> pipeline connection, preferably to the Northern Netherlands would be needed. For the all-electric scenario, finally significant imports of electricity are necessary, which would make a significant strengthening and expansion of high voltage electricity transmission necessary, probably northbound to future off-shore production in the North-Sea region.

The infrastructural challenges of the deep decarbonisation scenarios indicate an important challenge for far reaching mitigation strategies for industrial regions. As new technologies in industry need these infrastructures for operation but the new infrastructures also might require significant demand for the clean energy they are planned to deliver, both, infrastructure and decarbonised industry structures need to develop in parallel to some extent. This necessary harmonisation of both could be more pronounced for hydrogen as well as CO<sub>2</sub> infrastructures as these have to be newly developed almost completely (or converted). For natural gas and electricity on the other hand existing infrastructures can be used but could be

expanded stepwise as their use increases. These infrastructures are typically meshed with respective infrastructures in other neighbouring regions and some are used also for energy transit. This fact adds further complexity to the conversion.

Summing up, our scenarios for NRW show, that industrial regions face particular challenges to deep decarbonisation. To tackle these, more holistic scenario approaches are needed covering “normal” sociotechnical and economical aspects but also infrastructure needs and carbon balances of such regions.

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